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LoCuSS: Testing hydrostatic equilibrium in galaxy clusters

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ABSTRACT

We test the assumption of hydrostatic equilibrium in an X-ray luminosity selected sample of 50 galaxy clusters at $0.15 < z < 0.3$ from the Local Cluster Substructure Survey (LoCuSS). Our weak-lensing measurements of M_{500} control systematic biases to sub-4 per cent, and our hydrostatic measurements of the same achieve excellent agreement between *XMM–Newton* and *Chandra*. The mean ratio of X-ray to lensing mass for these 50 clusters is $\beta_X = 0.95 \pm 0.05$, and for the 44 clusters also detected by *Planck*, the mean ratio of *Planck* mass estimate to LoCuSS lensing mass is $\beta_P = 0.95 \pm 0.04$. Based on a careful like-for-like analysis, we find that LoCuSS, the Canadian Cluster Comparison Project, and Weighing the Giants agree on $\beta_P \simeq 0.9–0.95$ at $0.15 < z < 0.3$. This small level of hydrostatic bias disagrees at $\sim 5\sigma$ with the level required to reconcile *Planck* cosmology results from the cosmic microwave background and galaxy cluster counts.

Key words: gravitational lensing; weak – galaxies: clusters: general – cosmology: observations.

1 INTRODUCTION

Accurate measurement of systematic biases in galaxy cluster masses is fundamental to cosmological exploitation of galaxy clusters, as has been highlighted recently by Planck Collaboration XXIV

(2015b). Much attention has focused on the systematic biases in the respective mass measurement techniques, principally via weak-lensing (e.g. Okabe et al. 2013; Applegate et al. 2014; Hoekstra et al. 2015; Okabe & Smith 2015) and X-ray (e.g. Rasia et al. 2006, 2012; Nagai, Vikhlinin & Kravtsov 2007; Meneghetti et al. 2010; Martino et al. 2014) methods. Specifically, comparing lensing- and X-ray-based mass measurements tests the hydrostatic equilibrium assumption that underpins the X-ray-based mass measurements

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(e.g. Miralda-Escude & Babul 1995; Allen 1998; Smith et al. 2001, 2005; Mahdavi et al. 2008, 2013; Richard et al. 2010; Zhang et al. 2010; Israel et al. 2014).

Our goal is to assess the implications of the new Local Cluster Substructure Survey (LoCuSS) weak-lensing mass calibration (Okabe & Smith 2015; Ziparo et al. 2015) for hydrostatic bias and thus systematic uncertainties in cluster cosmology results. We combine the Okabe & Smith (2015) masses with hydrostatic masses from Martino et al. (2014). Both Okabe & Smith (2015) and Martino et al. (2014) control systematic biases in their respective mass measurements at sub-4 per cent. They are arguably the most accurate cluster mass measurements available to date. We also use mass estimates from Planck Collaboration XXVII (2015a) that assume hydrostatic equilibrium, via an X-ray scaling relation and measurements of the integrated Compton Y parameter from *Planck* survey data. We describe our analysis and results in Section 2, discuss our results in Section 3, and conclude in Section 4. We assume $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ throughout.

2 ANALYSIS AND RESULTS

2.1 Sample and mass measurements

The sample comprises 50 clusters from the *ROSAT* All-sky Survey catalogues (Ebeling et al. 1998, 2000; Böhringer et al. 2004) that satisfy: $-25^\circ < \delta < +65^\circ$, $n_H \leq 7 \times 10^{20} \text{ cm}^2$, $0.15 \leq z \leq 0.3$, $L_X[0.1-2.4 \text{ keV}]/E(z) \geq 4.1 \times 10^{44} \text{ erg s}^{-1}$, where $E(z) = \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}$. The clusters are therefore selected purely on L_X , ignoring other physical parameters. We focus on measurements of M_{500} , defined as the mass enclosed within r_{500} , i.e. the radius within which the mean density of the cluster is 500 times the critical density of the Universe (ρ_{crit}). M_{500} for a cluster at a redshift of z is therefore: $M_{500} = 500 \rho_{\text{crit}}(z) 4\pi r_{500}^3 / 3$.

We use weak-lensing masses from Okabe & Smith (2015, see also Ziparo et al. 2015). The two largest systematic biases in these weak-lensing masses are shear calibration (3 per cent) and contamination of background galaxy catalogues (1 per cent). The former calibration is derived from extensive image simulations, including shears up to $g \simeq 0.3$; the latter is based on selecting galaxies redder than the red sequence of cluster members using a radially dependent colour-cut. Okabe & Smith (2015) also used full cosmological hydrodynamical numerical simulations (Le Brun et al. 2014; McCarthy et al. 2014) to calibrate systematic biases in mass modelling to sub-1 per cent. In this article, we use weak-lensing mass measurements calculated after correcting for the shape measurements and contamination biases – see the Okabe & Smith (2015) table A.1.

We use hydrostatic masses from Martino et al. (2014), who modelled X-ray observations of the clusters assuming that the X-ray emitting cluster gas is in hydrostatic equilibrium with the cluster potential. 43 had been observed by *Chandra* and 39 with *XMM-Newton*. For the 21 clusters observed by both, the average ratio of *Chandra* to *XMM-Newton* hydrostatic mass was 1.02 ± 0.05 with an intrinsic scatter of ~ 8 per cent. We use hydrostatic M_{500} from table 2 of Martino et al. (2014), adopting masses from *Chandra* where available, and otherwise from *XMM-Newton* data. We add 8 per cent systematic uncertainty in quadrature to the statistical error on hydrostatic mass to account for the intrinsic scatter noted above. Note that Martino et al. (2014) use data from ACIS-I and ACIS-S on *Chandra* and EPIC (including both PN and MOS) on *XMM-Newton*.

We obtain estimates of M_{500} from Planck Collaboration XXVII (2015a) for 44 clusters. These masses are based on measurements of the spherical Compton Y parameter from the millimetre wave data, and a relationship between Y_X and M_{500} derived from X-ray observations of a sample of 20 clusters at $z < 0.2$ selected to have ‘relaxed’ X-ray morphology, where Y_X is the iteratively defined pseudo-pressure of the X-ray emitting gas, $Y_X \equiv M_{\text{gas}} T_X$ (Arnaud, Pointecouteau & Pratt 2007; Arnaud et al. 2010). As such, the *Planck* mass estimates assume the clusters are in hydrostatic equilibrium.

2.2 Method of calculation

We define β as the geometric mean ratio of the hydrostatic mass, M_{HSE} , to the weak-lensing mass, M_{WL} , for a sample of n clusters:

$$\beta = \exp \left[\frac{\sum_{i=1}^n w_i \ln \left(\frac{M_{\text{HSE},i}}{M_{\text{WL},i}} \right)}{\sum_{i=1}^n w_i} \right], \quad (1)$$

where w_i is the weight attached to each cluster. We calculate the uncertainty on β as the standard deviation of the geometric means of 1000 bootstrap samples each numbering n clusters. Measurements of β based on direct measurement of M_{HSE} from X-ray data are denoted as β_X , and measurements based on *Planck* mass estimates are denoted as β_P .

We aim to maximize sensitivity of the weights, w_i , to data quality, and minimize sensitivity to physical properties and/or geometry of the clusters. When calculating β_X we adopt the reciprocal of the sum of the squares of the fractional error on X-ray-based M_{HSE} (denoted here explicitly as M_X) and the absolute error on M_{WL} :

$$w_i = \left[\left(\frac{\delta M_{X,i} / M_{X,i}}{\langle \delta M_X / M_X \rangle} \right)^2 + \left(\frac{\delta M_{\text{WL},i}}{\langle \delta M_{\text{WL}} \rangle} \right)^2 \right]^{-1}. \quad (2)$$

The weighting with respect to the hydrostatic masses reflects the fact that the absolute error on M_X is tightly correlated with M_X itself. This is because the X-ray spectra of more massive (hotter) clusters contain less emission features than spectra of cooler clusters, thus making hydrostatic mass measurements intrinsically less precise for hotter clusters despite them being brighter. In contrast the fractional error on M_X is not a strong function of M_X , and so the mass dependence of the weighting scheme is significantly reduced. The weighting with respect to the weak-lensing masses reflects the fact that the absolute error on M_{WL} traces the weak-lensing data quality more faithfully than the fractional error on M_{WL} . Indeed, given the uniformity of our weak-lensing data (Okabe & Smith 2015), the fractional error would up-weight clusters with large values of M_{WL} , thus biasing our results to clusters with large masses and/or that are observed at small angles with respect to their major axis (Meneghetti et al. 2010). The latter effect would introduce a geometric bias into our results. When calculating β_P , we adopt the reciprocal of the sum of the squares of the absolute errors on M_{Planck} and M_{WL} :

$$w_i = \left[\left(\frac{\delta M_{\text{Planck},i}}{\langle \delta M_{\text{Planck}} \rangle} \right)^2 + \left(\frac{\delta M_{\text{WL},i}}{\langle \delta M_{\text{WL}} \rangle} \right)^2 \right]^{-1}. \quad (3)$$

The weighting with respect to the *Planck* mass estimates follows a similar motivation to that described above for the weak-lensing masses.

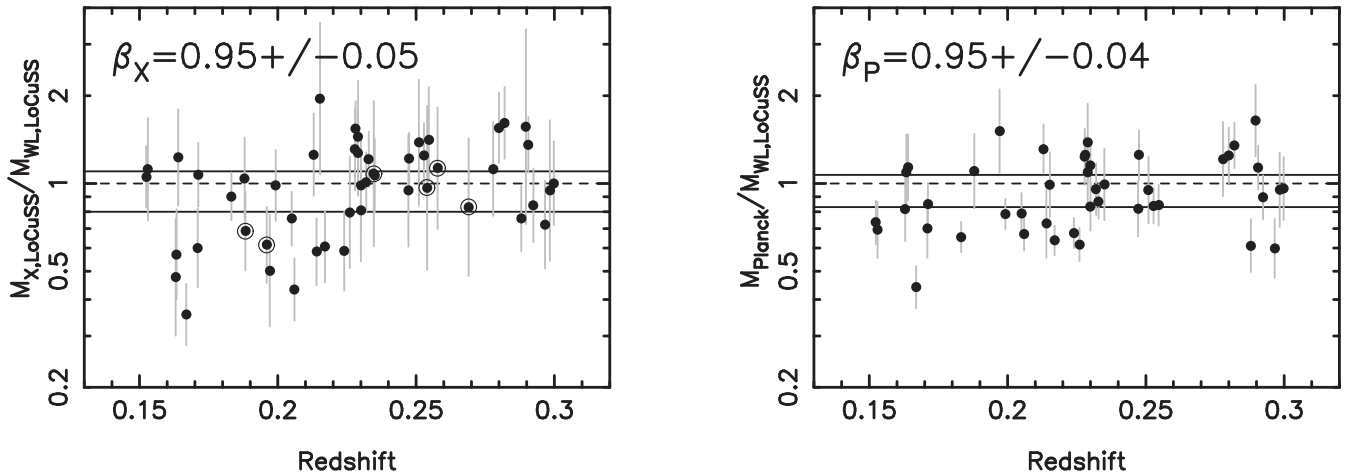


Figure 1. Left – Ratio of X-ray-based hydrostatic mass to weak-lensing mass versus redshift for the 50 clusters in the LoCuSS sample, adding an open circle around clusters not detected by *Planck*. Right – Ratio of *Planck* mass estimate to weak-lensing mass versus redshift for 44 clusters in the LoCuSS sample. Both – The Pearson correlation coefficient for mass ratio versus redshift confirms that the possible trend of mass ratio with redshift seen by eye in these panels is statistically insignificant. The horizontal dashed lines mark $\beta = 1$, and the solid lines show the $\pm 1\sigma$ confidence interval on β_X (left; Section 2.3) and β_P (right; Section 2.4).

2.3 Comparing LoCuSS weak-lensing and X-ray masses

We compare weak-lensing masses with X-ray masses, with each computed within their independently derived r_{500} (Fig. 1, left-hand panel), obtaining $\beta_X = 0.95 \pm 0.05$. Arguably a more accurate calculation uses hydrostatic and weak-lensing masses measured within the same radius. We therefore recalculate β_X based on X-ray and lensing masses both computed within the weak-lensing-based r_{500} (hereafter $r_{WL,500}$), obtaining $\beta_X = 0.87 \pm 0.04$, 1.2σ lower than the former measurement, however note that adopting $r_{WL,500}$ as the radius for both masses introduces a covariance that we have neglected in our calculation.

2.4 Comparing LoCuSS weak-lensing masses and *Planck* mass estimates

We compare weak-lensing mass measurements with the *Planck* mass estimates to compute β_P (Fig. 1, right-hand panel), obtaining $\beta_P = 0.95 \pm 0.04$, in excellent agreement with β_X (Section 2.3). Note that the apertures within which our weak-lensing masses are computed are independent of the apertures used by *Planck* Collaboration XXVII (2015a) when calculating the *Planck* mass estimates. We double check the consistency between β_X and β_P by repeating the X-ray/lensing comparison (Section 2.3) for the 44 clusters detected by *Planck* and considered in this section, obtaining $\beta_X = 0.97 \pm 0.06$. The agreement between β_X and β_P is therefore not sensitive to the six clusters that have not been detected by *Planck*.

3 DISCUSSION

We now compare our results with previous observational studies, noting in passing that our measurements of hydrostatic bias are in line with numerous cosmological numerical hydrodynamical simulations (e.g. Nagai et al. 2007; Meneghetti et al. 2010; Rasia et al. 2012; Le Brun et al. 2014).

3.1 Comparison with pointed X-ray surveys

Martino et al. (2014) compared their hydrostatic masses (used in this Letter) with LoCuSS weak-lensing masses (Okabe et al. 2010,

2013), obtaining $\beta_X \simeq 0.93$. This result is fully consistent with our $\beta_X = 0.95 \pm 0.05$, that uses the new LoCuSS weak-lensing masses from Okabe & Smith (2015).

The Canadian Cluster Comparison Project (CCCP) obtained $\beta_X = 0.88 \pm 0.05$ with both hydrostatic and weak-lensing masses measured within $r_{WL,500}$ (Mahdavi et al. 2013). Hoekstra et al. (2015) updated the CCCP weak-lensing masses, reporting masses [$M_{WL} (< r_{500})$] on average 19 per cent higher than Hoekstra et al. (2012) and Mahdavi et al. (2013). Applying a factor 1.19 ‘correction’ to the denominator of the CCCP β_X implies $\beta_X \simeq 0.74$. However, we note that Martino et al. (2014) found that the Mahdavi et al. (2013) hydrostatic masses are on average ~ 14 per cent lower than LoCuSS hydrostatic masses for 21 clusters in common (see Martino et al. (2014) for details). Applying a further factor 1.14 correction to the numerator brings CCCP up to $\beta_X \simeq 0.84$, in agreement with our $\beta_X = 0.87 \pm 0.04$ (Section 2.3).

Israel et al. (2014) considered eight clusters at $z \simeq 0.5$ from the 400 d survey, obtaining $\beta_X = 0.92^{+0.09}_{-0.08}$, in good agreement with our measurements. Note that this is based on the first line of their table 2, which gives the most like-for-like comparison with our methods.

After we submitted this Letter, Applegate et al. (2015) posted a preprint that compares weak-lensing and hydrostatic mass measurements within X-ray-based r_{2500} for a sample of 12 ‘relaxed’ clusters. Detailed comparison of their results with ours is hindered by the absence of individual cluster masses in Applegate et al. (2015), and their small sample. Their main result is a ratio of weak-lensing mass to hydrostatic mass within r_{2500} of 0.96 ± 0.13 . They also comment that they obtain a ratio of 1.06 ± 0.13 at r_{500} . We repeat our calculation of β_X described at the end of Section 2.3 within matched apertures with weak-lensing mass as the numerator and hydrostatic mass as the denominator, obtaining a weak-lensing to hydrostatic mass of 1.15 ± 0.04 at r_{500} .

3.2 Comparison with Sunyaev–Zeldovich effect surveys

Weighing the Giants (WtG) and CCCP have reported $\beta_P = 0.70 \pm 0.06$ and $\beta_P = 0.76 \pm 0.08$, respectively (von der Linden et al. 2014; Hoekstra et al. 2015), both based on the *Planck*

Collaboration XXIX (2014) masses. These measurements are lower than our $\beta_p = 0.95 \pm 0.04$ at 3.5σ and 2.1σ , respectively.

We apply our methods, including absolute mass errors weighting (Section 2.2), to the clusters and masses used by von der Linden et al. (2014), obtaining $\beta_p = 0.80 \pm 0.07$. von der Linden et al. (2014) do not state explicitly their method of calculation, however if we weight uniformly then we obtain $\beta_p = 0.69 \pm 0.07$, in agreement with them. Next, we update the WtG results to the Planck Collaboration XXVII (2015a) measurements of M_{Planck} , obtaining slightly higher values: $\beta_p = 0.72 \pm 0.07$ and $\beta_p = 0.83 \pm 0.07$ for uniform and absolute mass error weighting, respectively. Splitting the clusters into two redshift bins, with the lower redshift bin matching LoCuSS, and again using absolute mass error weighting, we obtain $\beta_p (z < 0.3) = 0.90 \pm 0.09$ and $\beta_p (z > 0.3) = 0.71 \pm 0.07$. This is consistent with our results at $z < 0.3$, and suggests β_p might be a function of redshift.

We also apply our methods to the clusters and masses considered by Hoekstra et al. (2015), obtaining $\beta_p = 0.83 \pm 0.07$. We reproduce the published CCCP result if we weight the clusters uniformly, in which case we obtain $\beta_p = 0.77 \pm 0.07$. Updating to the Planck Collaboration XXVII (2015a) masses, gives a slightly higher value of $\beta_p = 0.85 \pm 0.08$ (using absolute mass error weights). So far we have followed Hoekstra et al. (2015) in using their deprojected aperture mass measurements. However, both LoCuSS and WtG obtain masses by fitting an NFW (Navarro, Frenk & White 1997) model to the shear profile. To obtain a like-for-like comparison, we therefore use the Hoekstra et al. (2015) NFW-based masses, the Planck Collaboration XXVII (2015a) masses, and absolute mass error weights, obtaining $\beta_p = 0.92 \pm 0.08$. Finally, we split the CCCP sample into two redshift bins, as above, and find $\beta_p (z < 0.3) = 0.96 \pm 0.09$ and $\beta_p (z > 0.3) = 0.61 \pm 0.09$. This is consistent with our results at $z < 0.3$, again suggesting β_p depends on redshift.

After we submitted this Letter, Battaglia et al. (2015b) reported weak-lensing follow up of the Atacama Cosmology Telescope (ACT) thermal Sunyaev–Zeldovich (SZ) cluster sample. They commented that WtG and CCCP measurements of $\beta_p \simeq 0.7$ – 0.8 may be biased high because clusters that are not detected by *Planck* are excluded from their calculations. They estimated the possible bias by assigning to the non-detections a mass equal to the *Planck* 5σ detection threshold and thus including these clusters in the calculations of β_p . They found that this reduces the CCCP and WtG β_p values by ~ 0.06 and ~ 0.16 , respectively. We expect any bias of this nature to be small in our analysis because only six clusters from our sample of 50 are not detected by *Planck*. Nevertheless, we perform the calculations outlined by Battaglia et al. (2015b) and successfully reproduce their values for WtG and CCCP. We then estimated the possible bias in our results, and find that including the six non-detections reduces our measurement of β_p by just ~ 0.04 . We also estimate the bias for WtG and CCCP using just their clusters at $z < 0.3$, and obtain ~ 0.04 . Biases caused by excluding *Planck* non-detections appear to dominate neither our results nor comparison with WtG and CCCP at $z < 0.3$.

4 CONCLUSIONS AND PERSPECTIVE ON ‘PLANCK COSMOLOGY’

We have used three sets of independent mass measurements to develop a consistent picture of the departures from hydrostatic equilibrium in the LoCuSS sample of 50 clusters at $0.15 \leq z \leq 0.3$. These clusters were selected purely on their X-ray luminosity, declination, and line-of-sight hydrogen column density. The mass measurements comprise weak-lensing masses (Okabe & Smith 2015; Ziparo et al.

2015), direct measurements of hydrostatic masses using X-ray observations (Martino et al. 2014), and estimated hydrostatic masses from Planck Collaboration XXVII (2015a). The main strength of our results is the careful analysis of systematic biases in the weak-lensing and hydrostatic mass measurements referred to above, and summarized in Section 2.1.

We obtain excellent agreement between our X-ray-based and *Planck*-based tests of hydrostatic equilibrium, with $\beta_x = 0.95 \pm 0.05$ (Section 2.3) and $\beta_p = 0.95 \pm 0.04$ (Section 2.4). The masses used for these calculations are measured within independently derived estimates of r_{500} . We also remeasured β_x using X-ray masses measured within $r_{\text{WL},500}$, obtaining $\beta_x = 0.87 \pm 0.04$ (Section 2.3), suggesting that the actual level of hydrostatic bias, of astrophysical interest, might be slightly larger than inferred from the calculations based on independent measurement apertures.

Our measurement of β_p is larger (implying smaller hydrostatic bias) than recent results from the WtG and CCCP surveys (von der Linden et al. 2014; Hoekstra et al. 2015) at 3.5σ and 2.1σ , respectively (Section 3.2). However, if we restrict the WtG and CCCP samples to the same redshift range as LoCuSS ($0.15 < z < 0.3$), use a consistent method to calculate β_p (Section 2.2), and incorporate up to date *Planck* mass estimates (Planck Collaboration XXVII 2015a) into the WtG and CCCP calculations, we obtain $\beta_p (z < 0.3) = 0.90 \pm 0.09$ and $\beta_p (z > 0.3) = 0.96 \pm 0.09$, respectively. This highlights that the previously reported low values of β_p appear to be dominated by clusters at $z > 0.3$, with $\beta_p (z > 0.3) \sim 0.6$ – 0.7 . We also note that estimates of bias in β_p caused by excluding clusters not detected by *Planck* (Battaglia et al. 2015b) are ~ 0.04 for clusters at $z < 0.3$, and $\gtrsim 0.1$ at $z > 0.3$, in the sense that these biases reduce β_p . In short, any bias appears to be sub-dominant to statistical uncertainties at $z < 0.3$, that is the main focus of this Letter.

We are therefore lead to a view that $\beta_p \simeq 0.9$ – 0.95 at $z < 0.3$ and $\beta_p \lesssim 0.6$ at $z > 0.3$. The very low value at $z > 0.3$ could be caused by systematic biases in mass measurements that relate to observational or measurement effects, and not to the validity of hydrostatic equilibrium. It is plausible that systematic biases in weak-lensing mass measurements are better controlled at $z < 0.3$ than at $z > 0.3$, because for observations to fixed photometric depth, the sensitivity of the weak-lensing mass measurements to the accuracy of the redshift distribution of the background galaxies increases with cluster redshift. It would also be interesting to consider the possibility of redshift-dependent biases in the *Planck* mass estimates, and that β_p may indeed be a function of redshift (Andreon 2014).

Our results imply a hydrostatic bias parameter, $(1 - b)$, at the upper end of the range of values considered as a prior by Planck Collaboration XXIV (2015b) for their cluster cosmology analysis. Intriguingly, our measurements are compatible with the cosmic microwave background (CMB) lensing constraints of $(1 - b) = 1.01^{+0.24}_{-0.16}$ (Melin & Bartlett 2015), although the uncertainties on this pioneering measurement were large. On the other hand, our measurements disagree at $\sim 5\sigma$ with the value of $(1 - b) = 0.58 \pm 0.04$ computed by Planck Collaboration XXIV (2015b) as being required to reconcile the *Planck* primary CMB and SZ cluster counts. Moreover, the *Planck* CMB cosmology results are in tension with numerous independent large-scale structure probes of cosmology in addition to cluster number counts (e.g. Heymans et al. 2013; Mandelbaum et al. 2013; Beutler et al. 2014; McCarthy et al. 2014; Samushia et al. 2014; Battaglia, Hill & Murray 2015a; Hojjati et al. 2015; Planck Collaboration XXII 2015c), adding further indirect support to our results. It has been suggested that the *Planck* CMB/clusters tension might point to exciting new

physics, including possible constraints on neutrinos (e.g. Planck Collaboration XX 2014; Planck Collaboration XXIV 2015b). However, it is clear that significant further work is first required on systematic uncertainties in cluster mass measurement, especially for clusters at $z > 0.3$.

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